

STRUCTURES FOR THE 3RD GENERATION REUSABLE CONCEPT VEHICLE

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Abstract

A major goal of NASA is to create an advance space transportation system that provides a safe, affordable highway through the air and into space. The long-term plans are to reduce the risk of crew loss to 1 in 1,000,000 missions and reduce the cost of Low-Earth Orbit by a factor of 100 from today's costs. A 3rd generation reusable concept vehicle was developed to assess technologies required to meet NASA's space access goals. The vehicle will launch from Cape Kennedy carrying a 25,000 lb. payload to the International Space Station (ISS). The system is an air breathing launch vehicle (ABLV) hypersonic lifting body with rockets and uses triple point hydrogen and liquid oxygen propellant. The focus of this paper is on the structural concepts and analysis methods used in developing the 3rd generation reusable launch vehicle (RLV). Member sizes, concepts and material selections will be discussed as well as analysis methods used in optimizing the structure. Analysis based on the HyperSizer structural sizing software will be discussed. Design trades required to optimize structural weight will be presented.

Introduction

NASA is currently in the conceptual design phase for a futuristic 3rd generation RLV operational in the year 2025. The vehicle's major goals are to provide low-cost space access 100 times cheaper than present day shuttle costs as well as increasing flight safety. Achieving these goals will require advancing space launch technologies such as increased engine thrust/weight ratio, increasing vehicle life and maintainability, reducing structural weight and lowering production costs through reduced design complexity and tooling.

NASA has formed a Generation 3 Intercenter System Analysis Team (ISAT) to integrate system analysis capabilities and evaluate technology assessments that includes design tools and methods. One of these tools is a structural optimizing program called "HyperSizer" which is being used by ISAT to evaluate 3rd Generation structural concepts and demonstrate the program's fast sizing ability and design methodology. Structural weight reduction was performed without using a finite element based optimization procedure. Detailed structural concepts such as bladed stiffened, corrugated and isogrid panels were used in the design of a scramjet lifting body ABLV/SSTO (figure 1) carrying a 25,000-pound payload to the International Space Station (ISS) orbit.

NOMECLATURE

ABLV	Air Breathing Launch Vehicle
c.g.	Center-of-gravity
FEA	Finite Element Analysis
FEM	Finite Element Model
FWD	Forward
ISAT	Intercenter System Analysis Team
ISS	International Space Station
LH2	Liquid Hydrogen
RLV	Reusable Launch Vehicle
SSTO	Single Stage to Orbit
TPS	Thermal Protection System

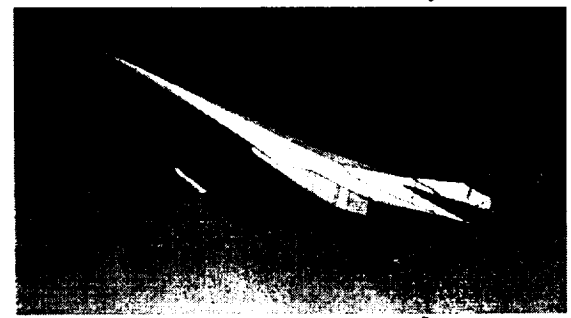


Figure 1. RLV/SSTO

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Aerospace Systems Concepts and Analysis Competency*
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Conceptual SSTD Design

The conceptual lifting body SSTD vehicle was used by ISAT as a baseline to test design and analysis methods used among the various NASA centers involved with aerospace vehicle designs. The overall dimensions of the vehicle are shown in figure 2. This study focused on the weight reduction and strength requirements of the major load carrying structural members.

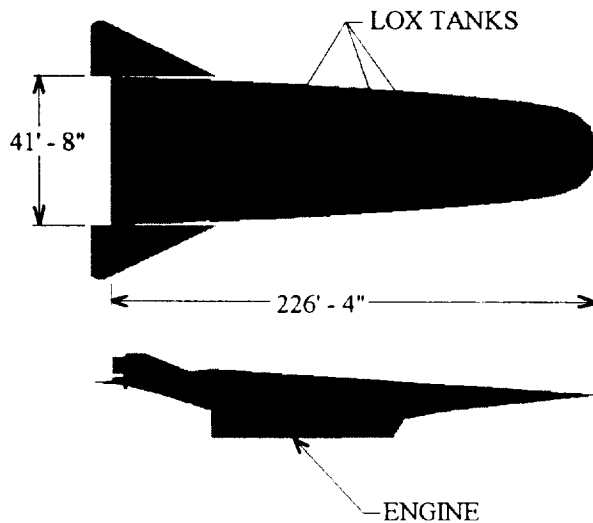


Figure 2. 3rd Generation SSTD

The SSTD lifting body, with its non-circular cross section, must be lightweight, fully reusable and easily maintained. A major challenge is to efficiently design the tank system necessary for an SSTD to gain ISS orbit.

Current tank system designs that were considered were the dual-lobed, such as in the X-33/RLV, and quad-lobed tanks. Each tank concept offered higher packaging efficient than circular tanks, but both still had large gaps between the vehicle outer mold line and the external surfaces of the tank structure. Also considered were conformal tanks that follow the outer mold line of the non-circular vehicle. They offer the most efficient use of internal volume but require high strength panels.

All propellants are LOX and LH2 with an approximate mass ratio of 3:1 respectively. Masses were estimated for the engine, control surfaces, landing gear and subsystems. Loading conditions were from a 1.5g vertical pull-up maneuver with a fully loaded

aerodynamically trimmed vehicle. The trimmed vehicle had the c.g. approximately at 55% from the leading nose edge.

The tank configuration chosen for the 3rd generation concept vehicle used conformal LH2 tanks and single lobed non-conformal cylindrical LOX tanks. Conformal tanks were originally chosen for the LOX but preliminary panel sizing of the outer skin panels of the vehicle revealed large weight gains were necessary to keep mid-span deflections minimal. The preliminary panel sizing is discussed later in this paper. The much lower density of the LH2 (4.75 c.f.) produced panel sizes that could support a conformal tank arrangement as shown in figure 3. The LOX tanks were pressurized to 20 psi and the LH2 tanks held at 5 psi.

The LOX was arranged into three tanks supported between the two keel beams as shown in figure 3. This arrangement allowed for the LOX tanks to be located near the vehicle takeoff c.g. and also allowed the LOX mass to help in trimming the vehicle when aero loads were applied. Conformal tanks were used for all LH2 and are also shown in figure 3. The tank positions were adjusted to keep the vehicle c.g. location near the 55% position. Bulkhead locations divided the fuselage into sections convenient for supporting tanks and defining the payload compartment. Structural supports for the main landing gear and nose gear were also included.

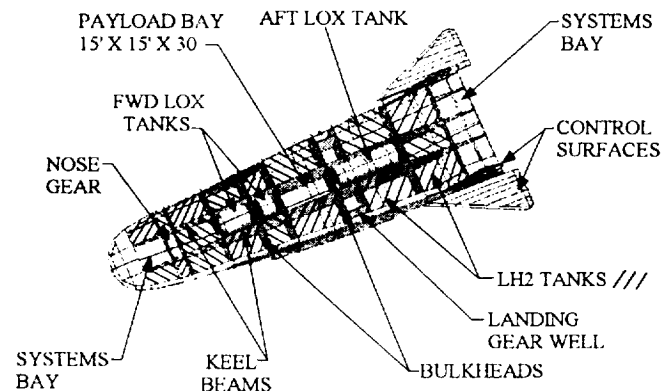


Figure 3. Vehicle Layout

The cryogenic fuels, LH2 at -423°F and LOX at -297°F , will create thermal gradients throughout the airframe and induce stress. Their contribution into sizing the airframe members were not considered in this study. The possible load paths produced from these temperature extremes could introduce load cases not allowed in this design. This would be a subject of greater interest in further detail analysis.

Structural Analysis Methods

The structural sizing of the SSTO 3rd generation concept vehicle was performed with a typical fea approach combined with a non-fea sizing program called HyperSizer. A finite element model of the vehicle was created using basic shell and beam elements. An asymmetry model was used with a coarse mesh as shown below in figure 4.

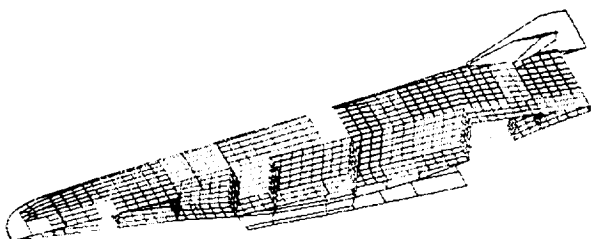


Figure 4. 3rd Generation Concept Vehicle finite element model

The purpose of the model was not to perform the structural sizing and optimization usually performed in aircraft weight reduction analysis but to import the model with all loads into HyperSizer. All sizing of the structure, which included margin checks, is performed inside HyperSizer. Optimization was achieved through HyperSizers approach to quickly identify the best panel or beam section as well as material selection.

Why use HyperSizer?

Aerospace structures contain complex geometry and load distributions that are highly indeterminate and historically demanded finite element analysis (FEA) to solve. Performing structural analysis and sizing optimization has required large degree-of-freedom models with long solution run times. A software product called HyperSizer can help simplify structural sizing and reduce design analysis time. HyperSizer helps to automate the sizing of structures by reducing flight and acceleration loads into force and moment components on panels and beams throughout the

vehicle. The sizing includes finding the optimal material combinations, panel and beam dimensions such as thickness, depths and spacing. The code is not a finite element analysis or computer aided design package. HyperSizer adds to the capabilities of these tools to allow the engineer to design, size and perform detailed failure analysis on a complete vehicle.

Optimization Capabilities

Optimization capabilities within HyperSizer include finding minimum weight panel or beam concepts, material selections, cross sectional dimensions, thickness and lay-ups from a database of 50 different stiffened and sandwich designs as well as a database of composite, metallic, honeycomb and foam materials. The database is used to define structural families inside HyperSizer. The structural families include definitions for panels and beams such as the "uniaxial stiffened family", the "unstiffened plate/sandwich family" and the "open beam family". The panels may be stiffened with typical aerospace shapes or corrugated as shown in figure 5. The grid-stiffened family of panels has recently been added to HyperSizer. This allows for the sizing optimization of isogrids, orthogrids and general grid rib-stiffened panel concepts with either isotropic or composite materials.

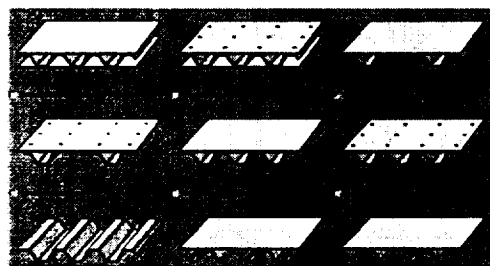


Figure 5. Corrugated panel concepts

The panels may also be sandwich shapes containing foam or honeycomb materials as shown in figure 6. HyperSizer adds flexibility to the optimization process by allowing face sheet and core thickness as variables used as an optimization parameter. The open beam family can be open or closed with both symmetric and unsymmetrical shapes. HyperSizer can limit an optimization to specific gages or specified material thickness if required during the design cycle. A stock list can be created to allow only members from the list to be applied to the current design variable.

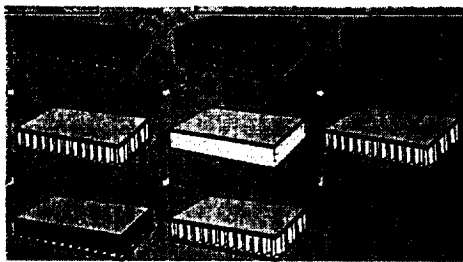


Figure 6. Foam and honeycomb panel concepts

HyperSizer Coupling with Nastran

The HyperSizer sizing software will solve problems with uniformly applied mechanical and thermal loads. These include in-plane shears, edge moments and in-plane or through-the-thickness temperature gradients. The code uses panel and beam forces and moments computed from nastran for sizing optimization and checking for failures in the structure.

HyperSizer uses equivalent panel formulations where complex 3-D panel shapes will be reduced to accurate 2-D planar elements. Equivalent 6×6 stiffness matrices are used in representing the group of finite elements making up the HyperSizer panel. The panels are represented in nastran by the `cquad4` and `ctria3` planar elements. The `pshell` card is used to define the properties for these elements and the `mat2` card is used to define the material properties. HyperSizer will automatically generate the generalized stiffness for the panels and export the appropriate `pshell` and `mat2` cards into separate files.

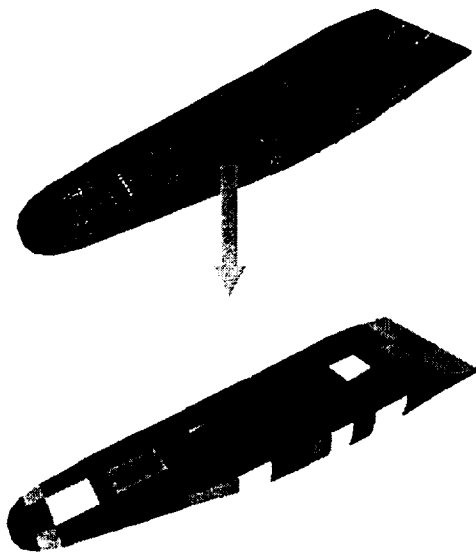


Figure 7. Fea to HyperSizer model

Figure 7 shows the 3rd generation concept vehicle fea model and how panels with similar properties are

grouped together into HyperSizer components. The HyperSizer model now has the necessary panel parameters to start sizing. To help narrow the selection of possible design choices, a preliminary panel sizing analysis was performed.

Preliminary Panel Sizing

An initial panel sizing was performed to help select possible candidate panel designs before the HyperSizer optimization process was started. The analysis was performed using HyperSizer's panel sizing analysis without fea. Panel sizing of the vehicle skins were performed to determine if conformal tanks could be used for the LOX and LH2. Figure 8 shows the typical trial panel geometry and loading used for the LH2 tanks. Estimates for N_x and N_y in-plane loads were derived from hand equations with an applied 5 psi internal pressure load. The panel width was held at 60" with span lengths varying at 30", 60", 90" and 120".

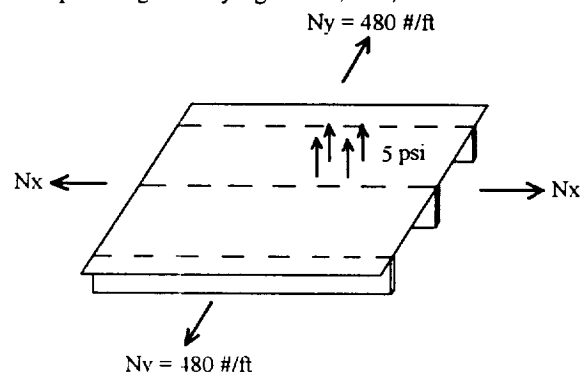


Figure 8. Bladed Panel used for Preliminary Sizing

Simply supported edge conditions were used to allow greater mid-span deflections. All mid-span deflections were held to 1% of the span length. The blade and skin thickness were given a range from .1 to .5 inches. Stiffener spacing was also allowed to vary from 4 through 20 inches. Strength and buckling margin checks were performed within HyperSizer and a 1.5 factor-of-safety applied. The trial panels tested were aluminum and graphite/epoxy.

Figure 9 shown below is the results for an aluminum bladed panel with 5 psi LH2 tank pressure. As spans are increased there is an expected rise in panel weight. Similar analysis for the 20 psi conformal LOX tanks showed excessive panel weights and growing sectional dimensions. The LOX conformal panels could not be efficiently designed for tank pressure plus the hydrostatic LOX head. The analysis, however, suggested that the LH2 blade stiffened conformal tanks

could be further improved upon. The next phase of the design was to take the preliminary panel sizing results and apply them to a fea/HyperSizer full model of the 3rd generation concept vehicle.

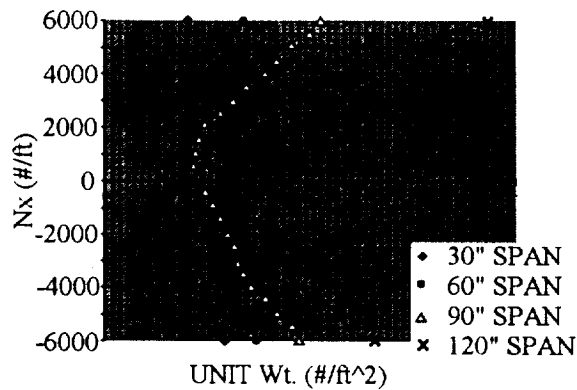


Figure 9. Bladed Panel Wt. Curves

Vehicle Analysis

The structural analysis on the 3rd generation concept vehicle was performed within HyperSizer. The major structural components were divided into skins, bulkheads and two keel beams as previously described. The various components of the vehicle, such as the keels and bulkheads shown in figure 10 below, were sized using different structure concepts. All metallic materials were first tried consisting of titanium and lithium aluminum. Problems encountered with the composite X-33 LH2 cryo tanks have prompted the use of metallic tanks for this study and an all-metallic airframe.

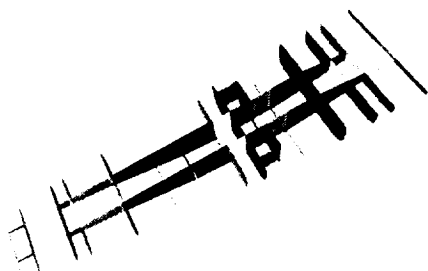


Figure 10. Keels and bulkheads

The initial material was all aluminum with 1" thick keels/bulkheads and a .1" aeroshell. The model is symmetric along the centerline with no control surfaces or engine geometry. These were modeled as lumped masses distributed at fuselage attachment points. Internal lumped masses were estimated for the LOX and LH2 tanks, landing gear, engine and sub systems. TPS sizing and thermal effects on the

structure were not considered during this study. Future enhancements to HyperSizer will combine TPS and panel sizing. This should greatly improve the preliminary design process for weight estimation.

The aero loading case considered was for a single point along a trajectory curve. The model was trimmed by moving the engine mass and calibrating the vertical force on the horizontal tails. A 1.5g vertical acceleration was also applied along with a factor-of-safety of 1.5 on the ultimate stress of the materials. Mid-span deflections limits were also held to less than 1% of the span length. The extensive flight envelope inherent in air breathing hypersonic vehicle designs involves many interdependent disciplines with large sets of control variables. The intent of this design study was to take a quick look at possible structural concepts due to a single worse caseload. A higher order analysis would require refinement of the loading definitions along many possible trajectory points and analyzing the vehicle as the cg changes with propellant use.

Supports for the LOX tanks were provide by a system of single degree of freedom connections as shown in Figure 11. The determinate connections allow for thermal displacements between the LOX tank and keel beams. The panels above the LOX tank as well as the payload doors were not included in the analysis. The panels were removed to provide access and possible tank replacement/inspection. The planform of the vehicle in Figure 2 shows the areas on the top surface where panels were removed. The continuous connection of the LOX access panels and payload doors to the adjoining structure could not be assumed and will certainly add conservatism into the analysis. The removal of the panels redistributes and increases bending loads into the keel beams and creates an open section for shear flows. It may be possible to design a mechanism for a continuous load path into the LOX access panels and payload doors, however such a design is left for future analysis.

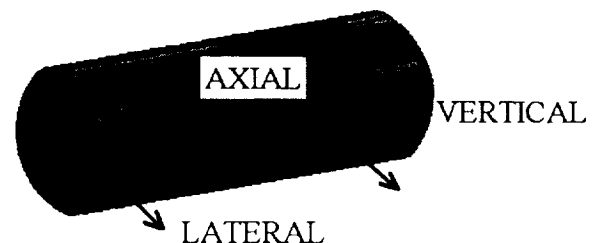


Figure 11. LOX tank support connections

Many margin checks were used during the analysis that included: panel and local buckling, crippling and strength checks. A relaxation of the panel buckling margins in the keel panel members could help reduce the section size. A separate fea, left for future analysis, would be necessary to allow diagonal buckling of the keel panels.

Results obtained from HyperSizer were compared to find an airframe structure producing the lowest weight and reasonable section geometry. The analysis varied combinations of the following structural concepts: bladed stiffened, corrugated and isogrid panels. Each combination produced different weights and load paths according to the panel stiffening method chosen. Some of these results are shown below in tables 1-3.

Table 1 shows the optimized structural sizing results for the bladed panel stiffening method. This method produced the heaviest airframe at 12.87 psf or 539,556 lbs overall. The blade thickness was allowed to vary from .1 to .5 inches and the depth from 1 to 12 inches. The skins were also given a range from .1 to .75 inches. Stiffener spacing was limited between 2 through 10 inches.



BHDS (bladed)	12.29 psf	116,114 lbs	21.51 %
KEELS (bladed)	15.94 psf	103,086 lbs	19.10 %
SKINS (bladed)	12.32 psf	320,376 lbs	59.39 %
Total Wt.	12.87 psf	539,556 lbs	

Table 1. Results for blade stiffen panels

Panels were grouped into optimization zones outlined by the keels and bulkheads. These structural zones represented the smallest practically manufacturable piece of the vehicle. HyperSizer was allowed to choose either integrally stiffened or "I" stiffened panels for the optimal design. Most panels chosen were the "I" stiffened type with aluminum skins and titanium stiffeners. HyperSizer could select titanium when higher strengths were required to support the larger LH2 volumes near the vehicle c.g.

Table 2 shows the results of isogrid keel panels and corrugated stiffened bulkhead and skin panels. The corrugated stiffening method lowered the weight for

bulkheads and skins by half. The dimensions of the isogrids were varied until an optimal size was achieved. Blade thickness and depths were varied for a general grid with both single and double face sheet. The corrugated stiffening method, chosen for the bulkheads and skin panels, used single and sandwich face sheets. Panel thickness, stiffener spacing and depths were also varied. Table 2 shows the panel concepts and the airframe weight of 7.24 psf or a total structural weight of 303,400 lbs.



BHDS (corrugated)	5.19 psf	49,018 lbs	16.15 %
KEELS (isogrids)	13.62 psf	91,770 lbs	30.25 %
SKINS (corrugated)	6.26 psf	162,612 lbs	53.60 %
Total Wt.	7.24 psf	303,400 lbs	

Table 2. Results for corrugated and isogrid panels

The final optimized corrugated panel designs were aluminum with skin thickness ranging from .1 to .5 inches and a core web thickness of .1 inch. A bottom sheet was selected by HyperSizer to achieve an optimal section. The spacing of the corrugation also varied between 4 and 8 inches and the depth ranging from 2 to 10 inches.

The isogrid structural concept, applied to the two keel beams, had web stiffeners running in three directions: fore/aft, vertical and diagonal. Structural weights were compared with the blade-stiffened concept that had only vertical stiffening. The final optimized isogrid reduced the design weight of the keels by 11,200 lbs. The added tridirectional stiffeners in the isogrid increased the bending stiffness to resist vertical inertial loads and the internal LH2 tank pressures. The isogrid keel design will also help in reducing thermal forces and moments induced from temperature gradients of the cryogenic fluids. The temperature effects are smaller for web-stiffened panels than they are for sandwich type panels.

The results for an all corrugated stiffened airframe are given in table 3. This stiffening method produced the lowest airframe weight of 6.05 psf or 253,512 lbs for the total structure. The corrugated stiffeners allowed the skins panels to carry greater bending

loads that helped to reduce the keel weights. Just as in previous stiffening methods, dimensions and number of face sheets were allowed to vary. This method produced an all aluminum structure with minimal thickness.



BHDS (corrugated)	5.13psf	48,550 lbs	19.15 %
KEELS (corrugated)	6.55psf	42,348 lbs	16.70 %
SKINS (corrugated)	6.26psf	166,612 lbs	64.15 %
Total Wt.	6.05 psf	253,512 lbs	

Table 3. Results for corrugated panels

Most of the skin panels were made up of .1 inch top and bottom aluminum face sheets and corrugated webs. The depth of the final panel size varied from 2 to 5 inches with the web core spacing of 4 inches. The keel panels required an increase in face sheet thickness to .25 inches and the depth range also increased to 8 inches.

Each stiffening method offered unique attributes for operating in a cryogenic environment. The uniaxial integral blade produced the heaviest airframe but would be the easiest to perform tank inspections. The corrugated panels are the lightest but could require lengthy inspection procedures. However, they could be used for insulation, fuel lines, piping and wiring.

Conclusion

The 3rd generation concept vehicle was analyzed using the HyperSizer structural sizing software. Preliminary sizing results for LH2 and LOX tanks showed conformal tanks could be designed for LH2 but not for LOX. The conformal LOX tank configuration had large panel displacements from the LOX inertia loads. The structure necessary for the panel displacements to be contained within margin created an unrealistic design. The displacements could be reduced with multiple tension membranes, however this also produced a heavy vehicle. Single lobed non-conformal LOX tanks were used but not sized in this study. Their mass contribution and tank reactions were included in the design. The analysis focused on sizing conformal tanks for LH2 and arriving at a preliminary structural weight estimate of the vehicle. Results for a 1.5g

vertical acceleration with a 1.5 factor-of-safety gave an optimized all aluminum structure built with corrugated panels. The final structural weight of the optimal design would be 253,512 lbs. for an overall fully fueled vehicle weight of 1,374,436 lbs. This included all mass estimates for the engine, fuel, LOX tank structure, control surfaces, payload and landing gear.

Analyzing the 3rd generation concept vehicle and optimizing the vehicle's design demonstrated the use of HyperSizer in a preliminary design. The software saved analysis time by performing margin of safety checks on the 3rd generation design without any modeling changes to the fem. Another time saver was that during the analysis only a coarse meshed fem was required. No detailed modeling of the stiffened panels was needed, just regular shell element properties. Engineering time was further saved by not running a fea buckling analysis and detailed panel sizing was quickly performed without a re-meshing of the finite elements. The benefits of HyperSizer were also shown in performing parametric studies on the conceptual vehicle design. The optimization process inside HyperSizer efficiently reduced the structural weight of the vehicle through selecting the best structural concept and giving optimal dimensions and material while performing strength and buckling margin checks.

No thermal effects were included during the structural sizing of the vehicle described in this paper. The next level of analysis would add temperature gradients from the aero-thermal loads on the outer skin panels and cryo temperatures along the interior panels of the conformal LH2 tanks. Determinate load paths from the LOX tanks were used to help isolate the tank and manage the degree-of-freedom of the thermal displacements. Single single-degree-of-freedom tank supports could be designed to allow thermal expansion/contraction and reduce stress concentrations at tank connections to the keels and bulkheads. Further use of isogrids will also help during a thermal analysis to reduce internal stresses and moments. No TPS sizing was performed however future upgrades of HyperSizer will allow TPS sizing and enhance the structural weight estimate.

HyperSizer is included in NASA's design methods for the 3rd generation RLV. The software's fast optimization ability will continue to be used as more generation vehicle concepts are reviewed and improved. The agency's ISAT team, which was established to evaluate and integrate analysis capabilities for aerospace technologies, has recognized HyperSizer as a modern structural sizing tool that can quickly improve weight and stiffness requirements for future vehicles.

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